# Evaluation of the SNR in the Echo-Shifted Pulse Sequence

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**INTRODUCTION** Echo-shifting (ES) pulse sequences [1-6] use an arrangement of additional gradients to delay the formation of an echo for one or more TR periods. For such pulse sequences, the effective echo time, $TE_{eff}$, is defined as the duration from the RF pulse to the corresponding "postponed" echo formed N TR periods following the selected pulse. Implemented within the skeleton of a balanced-SSFP pulse sequence, the ES formation mechanism allows the selection of the $TE_{eff}$ many-fold longer than the TR, while imaging artifacts usually associated with EPI sampling scheme are virtually eliminated. The ES pulse sequence confers an advantage of the substantially increased echo time without a severe penalty to the acquisition time. Moreover, in order to accommodate a given $TE_{eff}$ at larger values of N the TR has to become shorter thus reducing the acquisition time (TA). Such advantages can be successfully exploited in applications which require longer than usual echo times, such as the functional MRI. The strength of the MR signal detected at the $TE_{eff}$ depends on a particular ensemble of signal components that form the echo. The ensemble of component and their amplitudes are functions of N. Furthermore, the amplitude also bears dependence on the flip angle. It, therefore, is a substantial interest to evaluate the SNR and find optimal excitation flip angle as a function of N and estimate the sequence's time efficiency by evaluating the SNR/TA ratio. Such dependencies are discussed here.

**THEORY** The ES signal is a complex interplay of a great number of components of the MR signal. Indeed, since the effect of each RF pulse is tantamount to the application of three pulses, 0°, 90° and 180°, every spin population that existed prior to the RF pulse is partitioned into one transverse and two longitudinal components. Because of the additional echo-shifting gradients employed to introduce intentional dephasing over the TR period, the fresh transverse components originated from any given pulse do not contribute to the echo in the same TR period. Rather, each of these spin populations continues to develop affected by transverse and longitudinal relaxation respectively, and is further split again into three new partitions by the next RF pulse. Some of these components remained in the transverse plane, while other transitioned from the longitudinal to the transverse, and yet other – the other way. Immediately following the pulse, each of new transverse components possesses a certain amount of additional phase imparted by echo-shifted gradients during earlier TR periods. If such an additional phase is fully canceled by the echo-shifting gradient in the current TR, this component is rephased and contributes to the signal echo shifted in respect to the RF pulses which formed the now-rephased components. Thus, depending on the number of TR periods by which the echo is shifted, an incredible number of components with various amplitudes and weightings is created, intertwined and summed into the shifted echo by a series of RF pulses. Considered here is a balanced-SSFP pulse sequence that has been specifically modified with a periodical gradient scheme to enable an echo shift by an arbitrary number of TR periods. In such an implementation the number of TR shifts is determined by relative amplitudes of additional dephasing (D) and rephasing (R) gradients. Being of equal duration, these gradients have amplitudes according to this relation: $G_D/G_R=N/(N+1)$. This pulse sequence was used to evaluate the SNR as a function of the number of TR delays and the optimal excitation flip angle, which itself was expected to be a function of the N.

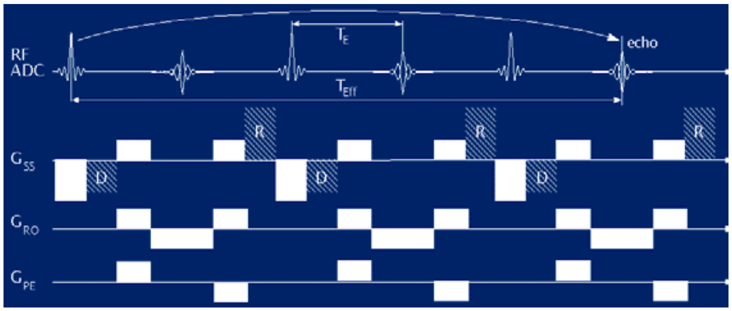

Figure 1. The pulse sequence design with offset R and D gradients

**MATERIALS AND METHODS** The balanced-SSFP pulse sequence was modified as shown in Figure. 1. The D and R gradients, shown shaded, were inserted between existing gradient structures along the slice selection direction. The final arrangement of gradients remained TR-cyclic. The phantom experiments were performed on a Siemens Sonata 1.5T instrument equipped with 40 mT/m-strong gradients capable of the maximum slew rate of 200 mT/m/ms. To preserve the symmetry of the sequence, the duration of R and D lobes were made equal and extended to cover the entire span of the "dead time" available in the sequence. The effective echo time was set to 50 ms. The amplitude of the R lobe was set to the maximum, while the amplitude of the D lobe was calculated from the ratio equation above to guarantee correct phase offset and thus the number of the TR shifts. For each value of N varied from 1 to 7 a series of measurements was taken with the flip angle varying from 1° to 90°, with an increased step in the range of the apparently lower signal. The SNR has been calculated for every measurement as a function of the flip angle, and the Ernst angle for each series has been noted. The time efficiency has been estimated by calculating the ratio SNR/sqrt(TA) in order to take into account square root dependence of the SNR on the number of averages, and thus the total acquisition time.

**RESULTS** The implemented sequence allows one to easily control the number of TR shifts and the evaluation of ES principles and effects. For all values of N the SNR exhibits an expected pattern with a single maximum at the Ernst angle, as shown in Figure 2. It can be observed from this figure that the SNR does indeed decrease as a function of N, with the Ernst angles also decreasing. Figure 3 shows the reduction of the SNR as a function of N evaluated at corresponding Ernst angles and a slight decrease of the time efficiency.

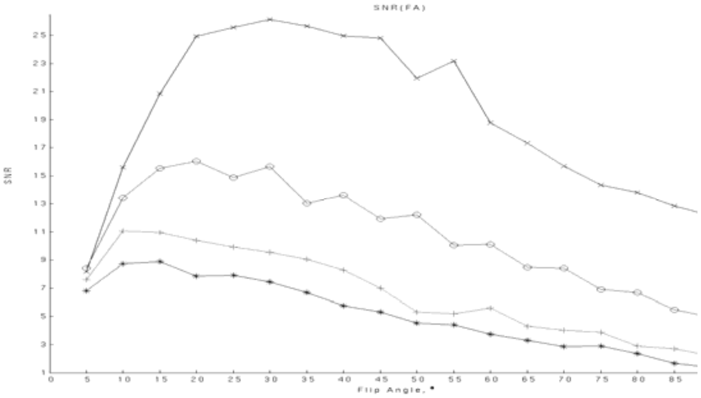

Figure 2. The SNR as a function of flip angle for various N

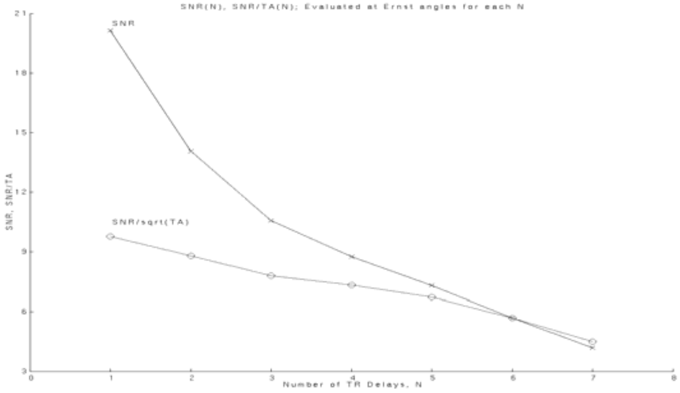

Figure 3. The SNR and time efficiency evaluated at Ernst flip angles.

**CONCLUSIONS** The decreased acquisition time favors the higher number of the TR delays. At the same time, however, the SNR, attained at the optimal flip angles, decreases as a hyperbolic function of the number of TR shifts, N. Because of such diametric behavior and due to the time efficiency being the highest for the N=1, there is an optimal trade-off between the value of N and the obtained SNR that has to be determined for every application at hand. For applications seeking the high SNR, it is recommended to keep the values of N at 1 or 2, while the value of N can be even higher in the applications that can afford to compromise the SNR for the shorter acquisition time. The evaluation results of this study can be applied to calculate optimal conditions for other echo-shifting gradient schemes.

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